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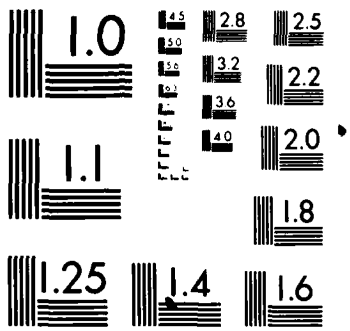

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ROBOTICS IN CONSTRUCTION

BY

MICHAEL R. BROZZO

A REPORT PRESENTED TO THE GRADUATE COMMITTEE
OF THE DEPARTMENT OF CIVIL ENGINEERING IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF ENGINEERING

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DEDICATED

TO

My wife, Nanette

and

my sons, Michael Jr. and Raymond

and

The United States Navy

TABLE OF CONTENTS

ABSTRACT

The potential use of robotics in building construction is examined. The origin of the words robot and robotics is provided. The four basic movements of the robots are identified to provide a visual representation of the motions involved. The basic components of a robot are broken down and discussed to provide a better understanding of this complicated piece of equipment. The building is broken down into basic components and then building activities are identified to construct these components and the performance requirements from a robot, necessary for their execution are specified. A description of four types of construction robots is derived from these performance requirements. The potential applications of the four types ~~of construction~~ robots are identified and discussed. Actual robotic construction applications, which are only practiced in foreign countries, are depicted and discussed. The social impact of robotics in construction is discussed, dealing with labor, unemployment and management attitudes. The economical impact of robotics in construction is analyzed and an example of a preliminary economic feasibility study is provided for informational purposes.

CHAPTER ONE
INTRODUCTION

1.1 INTRODUCTION

The manufacturing industries have long been enjoying the economic safety and quality benefits associated with robotization. However, the number of robots employed in United States construction is zero at the present. The reason for this lack of active interest in robotization of construction work is largely caused by the particular features of construction: the unique nature of every project, the production moving from one location to another, the divided authority over the project, the harsh environment and the volatile market. These features have always impeded the process of building construction.

Construction is the single largest industry in the United States' economy. Its output accounts for about 8% of the Gross National Product. It employs about 6% of the total labor force and its workers constitute about 10% of the blue collar workers. The private investment in construction accounts for 40% of the total private domestic investments. The construction industry is one of the least efficient industries as evidenced by its productivity decline of 1.5% annually over the last decade. Also, construction has a 40% lower output per worker than the industrial average. The work is strenuous and often performed under harsh and hazardous conditions. This is reflected in wages that are 50% higher than the industrial average. High insurance rates and large economic losses due to work accidents are a result of strenuous, harsh and hazardous conditions. All of these factors create an enormous potential for robotization with the expectation of productivity improvement.

The purpose of this paper is to provide a basic introduction to robots in general, identify building construction activities in which robots are capable of accomplishing, specify the basic types of construction robots, examine the general feasibility of robotic applications and identify some construction applications in which robotics are being utilized. This paper will provide sufficient information to justify the application of Robotics in Construction.

CHAPTER TWO
ROBOTS AND ROBOTICS

2.1 HISTORY

The word robot is based upon the Czechoslovakian word for slave and was introduced in a 1922 dramatization by Czech Karel Capek. The play was about mechanical men that rebelled against their human masters (1-5). The word robotics was coined by the science fiction writer Isaac Asimov, in the 1942 science fiction story, "Runabout." (2-3) From his story, the three laws of robotics were adopted. (2-4) They are:

1. A robot may not injure a human being, or, through inaction, allow a human being to come to harm.

2. A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.

3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.

Robotics is the science of designing, building, and applying robots. Robotics is a solid discipline of study that incorporates the background, knowledge, and creativity of mechanical, electrical, computer, industrial, and manufacturing engineering.

The international accepted definition of the robot was developed by the scientists at the Robotics Industries Association in 1979. They defined a robot as "a reprogrammable, multifunctional manipulator designed to both manipulate and transport parts, tools, or specialized manufacturing implements through various programmed motions for the performance of specific manufacturing tasks." (1-2) Further analysis will provide valuable insight into the implications of that definition.

The first key word is reprogrammable. This allows the robot to be programmed as many times as desired. The robot contains a program that is accessible, that can be changed, added to, or deleted, as the user chooses. There also can be many programs that would allow the robot to perform different functions in any sequence desired. In order for the robot to be programmable, it must have a computer that can be fed instructions and information. The computer can either be on-board the robot, or it can be in a remote location. This means that the computer controls the robot as long as the computer is able to communicate with the robot.

The next key word is multifunctional. This means that the robot is versatile and can perform more than one task. The same robot with a simple mechanical change of the ending tool can be used for various operations.

The third key word is manipulator. This means that the robot has a mechanism which allows it to move objects in the performance of its work. It is the manipulator that separates a robot from a computer.

Finally, consider the meaning of the phrase various programmed motions. This shows that the robot is dynamic; characterized by its continuous, productive activity.

CHAPTER THREE
BASIC ROBOT MOVEMENTS

3.1 GENERAL

Robots can be classified into four categories. They are classified by the nature of the movements that can be performed. The four categories of robots are: cartesian, cylindrical, spherical, and anthropomorphic. (1-10)

3.1.1 Cartesian

The cartesian or rectilinear coordinate system, as shown in Figure 1a, allows the robot movement in the classical three dimensional modes of in/out, up/down and forward/backward. (xyz motions by three sliding axes.) This motion system was one of the last to evolve.

3.1.2 Cylindrical

The cylindrical coordinate system, shown in Figure 1b, employs a cylindrical motion, whereby the x-y axis is rotated in space. (xy motion and rotary motion by two sliding axes and one rotary axis.) This system provides the robot with the ability to maintain an object in a parallel motion with the floor.

3.1.3 Spherical

The spherical coordinate system, shown in Figure 1c, consists of an in/out or extend/retract axis swung up or down, with the freedom to rotate. (one sliding axis and two rotary axes.) This was the first motion system utilized in robotics. The spherical system is easily mechanized and provides the robot with the ability to pick objects up from the floor.

3.14 Anthropomorphic

The antropomorphic or articulated system, shown in Figure 1d, is often referred to as human-like. This system allows the arm to sweep, the shoulder to swivel and the elbow to extend or retract. (one to seven or more rotary axes.) The advantage of this system is that it allows the robot to go past its central axis without rotating around its mounting. This was the last of the robot motion systems to come about.

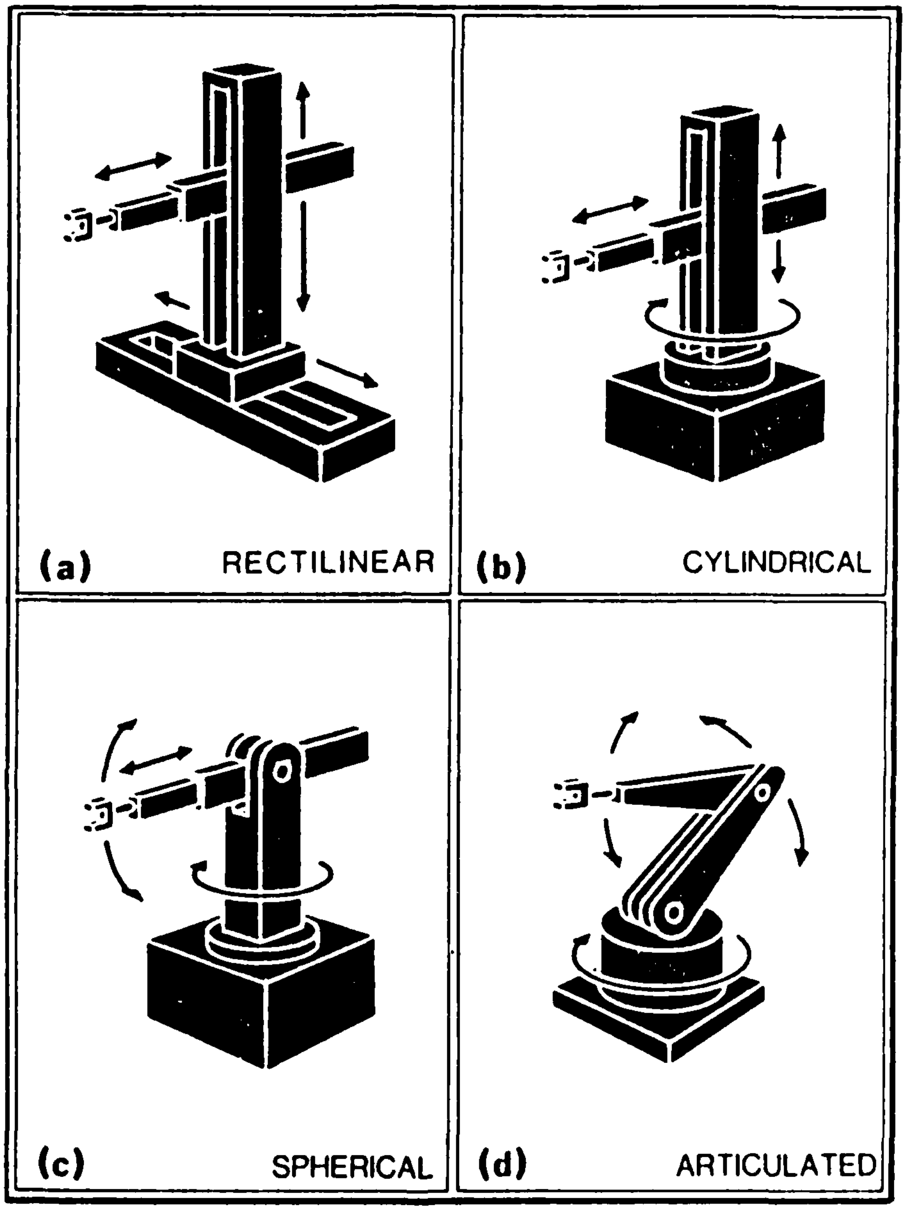

Figure 1 - Basic Robot Movements

Source: Ref. #3, Robotics, A User-Friendly Introduction.

CHAPTER FOUR
BASIC ROBOT COMPONENTS

4.1 GENERAL

The components of a robotic system can be grouped into six basic subsystems:

manipulator

controller

power unit

end-effector

sensory, and

mobility.

4.1.1 Manipulator

The manipulator is the arm unit and it comes in one of the four previously mentioned system configurations. With the arm, robots are able to manipulate or handle different objects by reaching and placing them at any location.

It should be noted that several types of construction equipment are similar in configuration to that of the regular robot manipulator. For example, most tower cranes can be viewed as manipulators with cylindrical configuration, gantry cranes as manipulators with cartesian configuration, and excavators as manipulators with a jointed configuration.

The length and strength of the arm and the speed of the robot determine the load that it can manipulate. Since the arm is a structure, it deflects under load conditions. In operations where tolerances are very small, the arm must be very precise in its movement and the allowable deflection of the arm approaches zero. The heavier the arm and the heavier the load, the greater the deflection; momentum and inertia usually translate into slower motions and lower precisions. Some arms are designed to move very rapidly over short distances with light loads. (3-31) Robot arms can handle hundreds, even thousands, of pounds. The reach of the robot arm affects the design and the precision of motion.

4.1.2 Controller

The function of the controller is to regulate the manipulator's movement and position by comparing the difference between the actual and calculated values and sending the signals necessary to make them match as much as possible. Robots utilize a variety of control methods. They are: manual control, fixed sequence, variable sequence, playback, numerical and artificial intelligence.

4.1.2.1 Manual Control

This method of control results from indirect human guidance or teleoperation. This particular type of remote control is already applied to cranes, concrete pumps, and excavating equipment.

4.1.2.2 Fixed Sequence Control

A fixed sequence of steps are built into the robot mechanical system. This mode of operation has limited application in construction due to the ever changing tasks and unstructured workplace.

4.1.2.3 Variable Sequence Control

Variable sequence control is a preprogrammed sequence of steps which can be changed from task to task.

4.1.2.4 Playback Control

Playback control is a type of control that allows the control unit to learn the desired sequence of arm movements as the arm is guided by the operator on the path of intended activity. The idea in this method is that the boundaries of the work segment will be learned by the robot on the spot and played back by its control system during execution. This type of control is achieved through combined man-robot teams where the robot performs the simple tasks specified by the defined boundaries, and man is more concerned with work planning, guidance, and execution of more involved finishing operations.

4.1.2.5 Numerical Control

Numerical control is a method of control in which the complete set of instructions are preprogrammed in a computer language which the control unit understands.

4.1.2.6 Artificial Intelligence Control

This is a method of control in which a preprogrammed sequence of steps are modified as a result of the robots interaction with the environment. Signals from the environment are received by transducers and transmitted to the control unit. The transducers react very similar to the human senses of vision, hearing and contact. Interpretation of these signals and the resulting reaction requires a degree of artificial intelligence be built into the control unit. The artificial intelligence is a computer program that provides the required reaction. The computer program must have a high speed reference memory that contains all of the data necessary for a specific problem or an optimization situation. Also, the computer program must be able to update and streamline the reference memory to improve the performance of the original program for the next problem or procedure. Finally, the computer program must be able to perform the following sequence of events: accept input data, compare data with the reference memory, use the determined procedures to solve problems or improve performance over known data, compare outputs to determine if the situation problem or performance was improved, store the comparison in the refernce memory and take action based upon the comparison. (4-264)

Expert systems, considered part of artificial intelligence, are systems capable of handling real-world complex problems requiring an expert's interpretation. Also, they solve these problems by using a computer model of human reasoning, reaching the same conclusion that the human expert would have reached if faced with the same situation. (5-53) These systems are just now coming into the marketplace and should begin to impact the robot industry in the near future.

4.1.3 Power Unit

The power unit is required to move the robot and payload through the desired motion. There are three basic types of power units: hydraulic, pneumatic and electric. The power unit is generally one of the three or a combination of the three.

4.1.3.1 Hydraulic

Generally, the hydraulic power unit is utilized on the larger robots that handle heavier loads. This creates some limitations on speed and type of motion. Hydraulic systems can move only in two directions, along a straight path. Angular motion can be created by using a hydraulic cylinder to open or close a hinge-like joint. There are some disadvantages in using hydraulics as a power unit. One disadvantage is the requirement for a heavy pumping and valve system. Another disadvantage is that the hydraulic system employs pressures that could be of a safety concern. Finally, most hydraulic systems eventually leak fluid which could become a problem.

4.1.3.2 Pneumatic

The pneumatic power unit is used for the simple pick-and-place robots. Pneumatic power units are well suited for the factory environment, which has a readily available supply of compressed air. Pneumatic systems do have a drawback. Pneumatic systems exhaust air, which contains possible contaminants of water vapor and oil mists, into the load environment.

4.1.3.3 Electric

The electric power unit is utilized in medium weight applications where there is a requirement for highly accurate work. Direct current motors are being designed to meet a wide range of power requirements. These motors are very inexpensive and extremely reliable. The electric motor could be a spark hazard in an environment that contains explosive mixtures.

4.1.4 End Effector

The end effector is the device utilized by the robot to perform the particular task for which it was designed. End effectors come in a variety of options to provide versatility. End effectors can be divided into two types; grippers and process tools. The end effector is positioned and oriented by the manipulator, and their operation is triggered by an off/on command from the control unit. Some end effectors can be activated directly from the sensors attached to them. The quality of the end effector's performance depends upon the manipulator's positioning tolerance, the working tolerance of the tool, and the interaction between the sensory device and the environment. More than one type of end effector can be used simultaneously on the manipulator's arm. They can be changed by a human operator or by another robot.

4.1.4.1 Grippers

Grippers are two or more fingered devices designed to grasp an object similar to a human hand. Grippers are used in pick-and-place operations where objects are grasped and transferred to another location and released. The grippers are suited to the shape of the object to be handled. The more popular grippers are finger grippers, suction grippers (for flat or smooth objects), magnetic grippers (for metallic objects), and tube grippers (for hollow circular tubes). (6-41)

4.1.4.2 Process Tools

A process tool is an end effector attached to the wrist of a robot in order to accomplish a specific task. Typical process tools for most applications are the welding gun, paint sprayer and grinding disk. Other process tools, pertinent to building operations, could be used for spreading glue, mortar or concrete, sealing joints, troweling, smoothing and sand blasting. (4-263)

4.1.5 Sensors

People are able to survive in harsh environments by the use of the five senses; sight, hearing, taste, smell and touch. By using sensory transducers, robots are capable of serving such environments. The transducers convert physical effects; mechanical, optical, electrical, acoustical, and magnetic, into electronic signals which can be recognized and acted upon by the control unit.

Sensors are very important in building operations because they convey real time information to the control unit, concerning the main features of unstructured and changing building environments. The more important group of sensors to building construction are the tactile, proximity and vision sensors.

4.1.5.1 Tactile Sensors

Tactile sensors indicate contact with an object or relay the extent and the direction of force exerted during the contact. This sensor will prevent collisions between the robot's arm or body and the object to be handled or part of the structure. The contact is sensed by the transducer, and a warning signal is sent to the control unit. Also, this sensor can be used for verification of the required preprogrammed work path. Deviation from the prescribed path would cause a change in the interacting forces resulting in a warning signal being sent to the control unit. (4-266)

4.1.5.2 Proximity Sensors

Proximity sensors detect the nearness of objects and determine the location and the range of objects. This sensor is useful in the verification of work quality and its conformance to specifications. This can be accomplished by either an ultrasonic or an electromagnetic sensor when inspecting the thickness of coating. (4-266)

4.1.5.3 Vision Sensors

Sight is the most important of the sensory capabilities for a robot. The vision sensors react to light reflected from other objects, the sensinq signals are translated into images, with the aid of artificial intelligence. Vision sensors can be utilized for the inspection of textured surfaces and the examination of exterior dimensions of a product. Vision sensors will be instrumental in the navigation of the robot's arm or body towards a desired location. (4-266)

4.1.6 Mobility

Almost all of the robots in industry today operate from a fixed position. But in construction, the location of the work changes continuously and therefore the robot must be able to move or be moved, from one location to another.

Robots use wheels, treads, and legs to move from place to place. By means of direct or remote control, robots can be transferred from one station to another. The ideal situation is for the robot to be preprogrammed to follow the desired route. At the contruction site, robots encounter rough terrain, changing dimensions, and obstacles along the path. These situations require the robot to be in continuous interaction with the environment. By employing sensors, which can record the specific features of the environment, the robot is in continuous contact with the surroundings. Another way of getting the robot around the construction site is by guiding the robot along a prepositioned electric or steel wire. With the electric wire, the sensors are electromagnetic and with the steel wire, the sensors are potentiometers or strain gages.

CHAPTER FIVE
ROBOTICS IN CONSTRUCTION

5.1 GENERAL

There are no construction robots being manufactured for mass distribution at the present time. Until recently, construction robots were not seriously considered. The reason for the non-existance of construction robots can be attributed to the ideals and opinions expressed by the robot manufacturers. According to David M. Osborne, of Swedish ASEA's office, "construction jobs are not always the same, so there's not a great deal of repeatability. Most construction jobs require a certain amount of on-site judgement, which a robot can't provide. And there are a lot of uncontrolled environmental factors." (7-191) Also, David Wisnoski, of Industrial Systems Group, commented that "where robots work best is where the environment is very structured. The construction industry is very individualistic and resists this kind of thing. I wouldn't say people should be worried about their jobs yet - there won't be robots in their business for quite some time." (7-191). These expressed attitudes are quite surprising, it would seem that robot manufacturers would accept the challenge to robotize construction rather than become so easily discouraged. However, the enormous size of the construction industry and its dependance upon manual labor, creates an obvious potential for any type of robotization of building construction.

5.1.1 Building Construction Activities

The potential for robotization of the construction industry can be better realized by breaking the building down into components and then matching the components to basic construction activities which can be performed by robots. The major components of a building are: substructure, framing, horizontal space dividers, exterior walls, partitions, exterior wall finish, interior wall finish, flooring, roofing, mechanical systems and electrical systems. The construction of these components can be broken up into eleven types of basic activities. They are, as shown in Table 1, positioning, connecting, attaching, finishing, coating, concreting, building, inlaying, covering and jointing. (7-74) The activities were developed with the idea that each activity could be performed by a single robot with the same effector and mode of operations. These activities can be further divided into three main groups:

The first group of activities involve the covering or conditioning of continuous sur .ces. Examples of this task are; painting, spraying, plastering, trowelling, spreading of mortar, cleaning and sandblasting. These activities can be performed, without any difficulty, at the present stage of robotic technology.

The next group of activities involve moving the effector at different locations in a predetermined pattern, either linear or point to point. Examples of this task are; welding, bolting, taping, jointing, grouting, and spreading of resilient material rolls for flooring and wall coverings. These tasks can also be accomplished without particular difficulty at the present stage of technology if the dimensions of the structural element can be precisely learned and if the access points for the robot can be

Table 1 - Basic Activities in Building Construction

No.	Activity	Description	Examples of application
1	Positioning	Placing a large object at a given location and orientation	Erection of steel beams, precast elements, formwork, scaffolding
2	Connecting	Connecting of a component to an existing structure	Bolting, nailing, welding, taping
3	Attaching	Positioning and attaching of a small object to an existing structure	Attaching hangers, inserts, partition boards, siding, sheathing
4	Finishing	Applying continuous mechanical treatment to a given surface	Trowelling, grinding, brushing, smoothing
5	Coating	Discharging a liquid or semiliquid substance on a given surface	Painting, plastering, spreading mortar or glue
6	Concreting	Casting of concrete into molds	Casting of columns, walls, beams, slabs
7	Building	Placing blocks one next or on top of the other with a desired pattern	Blocks, bricks or stones masonry
8	Inlaying	Placing small flat pieces one next to the other to attain a continuous surface	Tiling, wood planks, flooring
9	Covering	Unrolling sheets of material over a given surface	Vinyl or carpet flooring, roof insulation, wall fabric
10	Jointing	Sealing joints between vertical elements	Jointing between precast elements, between partition boards

Source: Ref. #14, Economic Implications of Robotics in Building, Page 74 concisely determined. Due to uncertain building conditions, the robots must be either guided by humans or be equipped with sensory devices to monitor its performance.

The final group of activities involve handling, positioning, and assembling large and small building components such as structural steel, precast elements, timber planks, formwork, scaffolding, siding and pipes. These activities are the most difficult for robotization because they involve the very precise storage of often bulky components, the careful multi-axis manipulation and the accurate orientation and positioning of building components. This is the most difficult area for robotics because in order to satisfy the requirements of these activities would be quite involved and quite costly.

5.1.2 Construction Robots

Through careful consideration of the building construction activities, it can be determined that most building construction operations can be performed by four basic types of robots. The four basic types of robots, as shown in Figure 2, are: assembly robot, general purpose robot, floor finishing robot and exterior wall finishing robot.

5.1.2.1 Assembly Robot

This robot would be used for hauling and positioning large building components, such as; steel beams, precast concrete members, and partially assembled formwork. The manipulator would be an anthropomorphic arm, similar to the arm of an excavator, with a reach of 65-80 feet and a payload of 1-3 tons. The arm must have 3 to 4 degrees of freedom or movement, with an additional 2-3 degrees of freedom at the wrist for orienting and precise positioning. (4-269) The manipulator can be in a fixed position or placed on a mobile platform.

The end effector used for this robot could be finger hooks, suction grippers or magnetic grippers. The type of grippers utilized will depend on the type of objects it will be used upon. The objects to be handled should be carefully stored on the site, either on trucks or in containers, in a pattern that will be easily recognizable by the control unit.

Control of the robot can be accomplished by way of teleoperation or preprogrammed and monitored by sensors. The pick and place activities on the construction site could be made easier by pre-marking components for recognition by the robot's sensor system.

This system is most advantageous when utilized under harsh or hazardous conditions. Under these circumstances, the robot's dependence on human assistance must be nonexistent.

5.1.2.2 General Purpose Robot

This robot will be used for all building interior operations which can be performed from temporary static work stations. Examples of these operations are painting, grouting, nailing and bolting.

The robot will function from a temporary fixed position. The manipulator will be an anthropomorphic arm with 5-6 degrees of freedom and a reach capability of 10-14 feet. (4-270) The smaller reach dimension is necessary to reach every point on an interior wall of a usual commercial, public, or residential building. The larger reach dimension is necessary to be able to operate from the same location in a regular roomsize area. A manipulator with a reach greater than 14 feet would be difficult to manipulate within the confines of a regular building. Also, the lifting capacity of the arm should be sufficient to support the weight of the heaviest tool or interior building component.

The robot can use a variety of end effectors, for instance, drillers, spray guns, and grippers. The type of end effector will depend on the operation for which it will be utilized. For operations requiring a continuous supply of material, plaster, paint or grout, it will be supplied from a canister mounted near the manipulator or for the case of liquid material, pumped from an external source.

The mode of control can be accomplished by two methods. It can be preprogrammed with respect to operational pattern of the effector or it can be led through the tasks it is to perform. Also, the two modes can be combined, where the leading through mode is confined to the critical points and the preprogrammed mode will accomplish the rest of the work. In addition, the control should be complemented by real time feedback from the operation provided by vision, contact, or proximity sensors.

The mobility of the robot can be accomplished manually, on wheel or tread mounted carriages, by teleoperation or with the aid of an automatic navigation system. The manual transfer will be accomplished by means of a small crew working in the vicinity and using the robot as a helper. Teleoperation is accomplished by a single human operator monitoring the operation of several robots on the job site. The self navigating robots use sensors, either rotating vision or sonar. The workplace can be rigged to provide a path for the robot to follow.

5.1.2.3 Floor Finishing Robot

The floor finishing robot would be used for horizontal finishing operations, such as, trowelling, glue spreading and brushing. This robot would be most useful on large floor areas. The robot will have an effector attached to a mobile platform which will be applied directly to the floor underneath. The movement of the effector will be effected through the movement of the carriage. The effector can be a trowel, hose or gun. The finishing material will be stored on the carriage, in a mounted canister. (4-271)

The robot will be teleoperated to move over the required work area, or preprogrammed and led through the critical points. Movement of the robot within the work area can be controlled by limit switches which are activated by contacting a temporary barrier erected on the perimeter.

5.1.2.4 Exterior Wall Finishing Robot

This robot will be used for finishing activities, such as painting, plastering, weatherjointing and final inspection of large exterior building areas.

The robot will have a vertical carriage suspended from the roof's parapet and an effector mounted between it and the wall surface. The carriage will cover vertical strips, being moved up and down the wall while the effector moves vertically with the carriage, and have some horizontal freedom in order to cover a width of 6-13 feet. (4-271) The effector can be pressed towards the wall surface using vacuum grippers attached to the carriage.

The robot can be teleoperated or preprogrammed for the specific task and desired area. Also, the robot can be monitored by the feedback from vision or contact sensors.

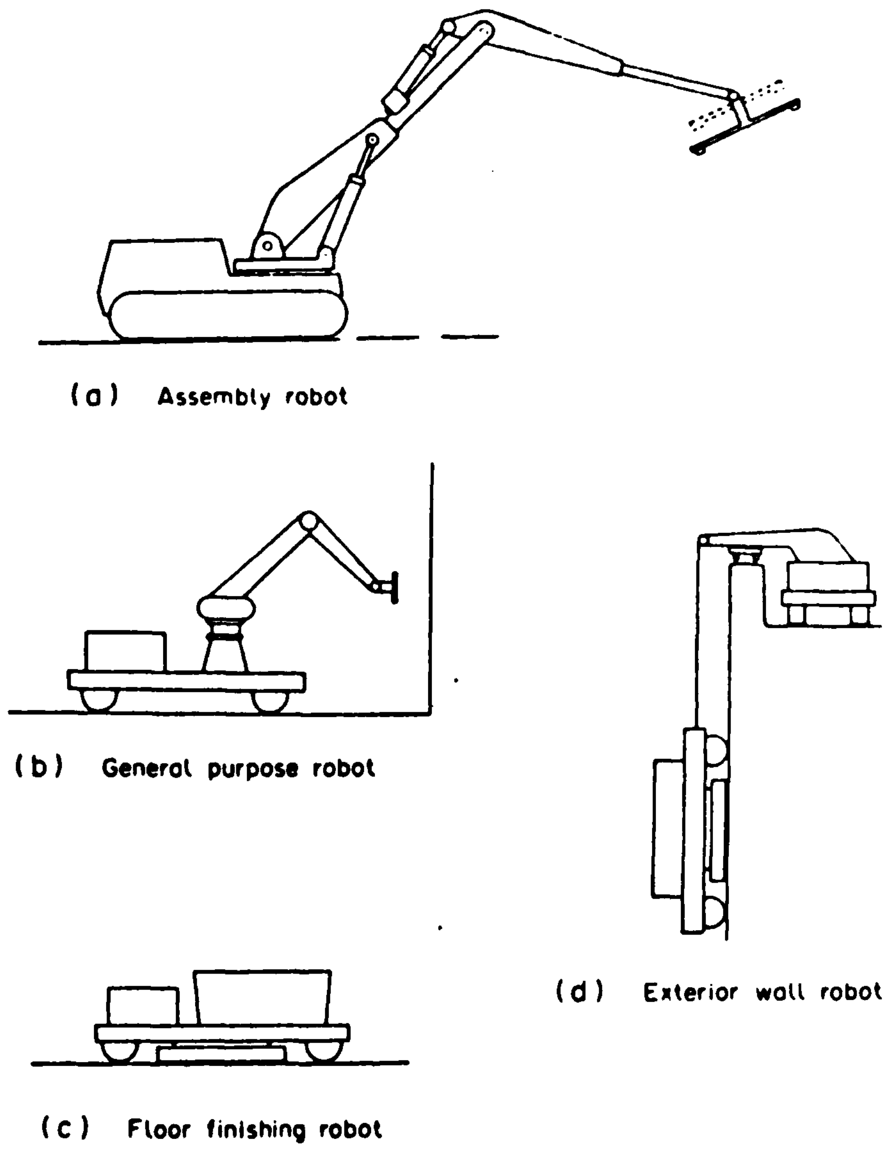

Figure 2 - Construction Robots

Source: Ref. #14, Economic Implications of Robotics in Building Page 75

CHAPTER SIX
POTENTIAL APPLICATIONS IN CONSTRUCTION

6.1 GENERAL

The potential applications of the four previously mentioned robots are limited only by the willingness of the manufacturers and desires of the construction industry. The technology and expertise exists for the production of construction robots. The employment of the robots can follow one of two possible patterns. The robots can be used either for the execution of single tasks or within a framework of minimum human involvement. The second case involves the use of computers for planning and monitoring robotized construction work.

6.1.1 Single Task Applications

Robots performing single tasks will be most effective with a certain degree of human intervention. This can be accomplished by teaching the robot the outer limits of the work area, by guiding the robot through a teleoperator or by physically moving the robot from one station to another.

6.1.1.1 Material Handling and Positioning

Handling materials is the largest part of construction work. The assembling robot, shown in Figure 2a, will pick up the materials and place them at the precise location and orientation on the structure. Also, the robot would be able to keep an inventory of the materials.

This real time inventory is extremely helpful in the material requisition and distribution process. The use of robotics will reduce the labor requirements over that of a conventional crane. The conventional crane requires hook up time as the materials are attached, materials orientation on the building and temporary support. (7-274)

6.1.1.2 Painting Exterior Walls

This is one area where robots have proven to be very effective. The robot will perform this task from a stationary work station inside a room and then be moved to another station by a human operator. The operator will define the configuration of each station to be painted, to the robot. Special attention will be given to the critical points, corners, windows, and doors, by guiding the robot's arm through these points. Once the robot is properly taught, it can do a better and more consistent job than humans. The robot can also be programmed to trim the edges around the doors and windows with a brush. Other interior activities such as wall papering, welding and taping of joints, can be performed in the very same manner. (7-275)

6.1.1.3 Plastering Exterior Walls

This robot, shown in Figure 2d, would be mounted on the roof parapet by a crane and human operator. The plastering material would be pumped into an attached canister. The canister would have an automatic control to measure flow and consistency.

The robot would move in a vertical direction and do the plastering one strip at a time. The limits of the area to be plastered could be defined by coordinates programmed into the control unit or the limits could be determined by prepositioned fixtures interacting with contact or proximity sensors. (5-53)

6.1.1.4 Spreading Flooring

This robot, shown in Figure 2c, would accomplish its task by moving twice over each strip of floor. On the first pass it would smooth the surface and spread the adhesive underlayment. With the second pass, the robot spreads the rolls of flooring material and seals them to the base. The robot would do a more consistent job than humans by very closely controlling the consistency of the adhesive, the amount of adhesive and the tension on the flooring material. This task can be performed by the robot itself or with a human operator. If the human operator is utilized, he can be seated on the carriage and move with the robot. (5-52)

6.1.1.5 Concrete Floors

The robot, shown in Figure 2c, could be used to finish concrete floors. The robot could use laser beams to obtain concrete floors that properly slope toward the drains. Laser systems would also be useful to level floors. This robot can be used in conjunction with a teleoperated arm. The arm can be used for the casting of pumped concrete and could have additional tools attached for compacting, vibrating or leveling. (5-53)

6.1.1.6 Planning for Robotization

The construction industry requires a great deal of planning and scheduling. To make use of robots effectively on the construction site, there must be a great deal of careful planning. The types and numbers of robots to be used must be carefully considered. The tasks and work areas assigned to each robot must be carefully laid out to ensure safe movement patterns of each robot between the work stations. All of the critical points must be considered and defined to each robot for each work station. Probably the one task that requires the most planning is the proper location of working materials for each task and working area.

6.1.2 CAD-CAM Application

The use of robots in a building project will involve a considerable amount of planning. Through the use of prefabricated components, specially adapted for robotic handling, the robotized construction process would be more efficient. The robotic construction process design can be most effective when performed for multiple applications within the framework of a closed system with an integrated authority over the design of buildings, the prefabrication of their components, and their assembling and finishing on the site. (4-276) This type of system would benefit from the assistance of computer-aided design and computer-aided manufacturing procedures.

This system would evolve around standard prefabricated building components, such as exterior walls, stairs, sanitary units, and floor slabs. Each fabricated component would contain the necessary elements. Those elements would be carpentry, electrical connections, plumbing fixtures, finishing works, and temporary supports. The components would be designed with consideration given to the type of building, and the features of the robots utilized for assembling and finishing.

The group of elements for a single building would be the easiest to develop and then duplicate the design many times at various locations. The design of this building would involve the structural prefabricated components, the finishing work on the site and the complete procedures for robotization. The robotization planning would include types of robot, robot tasks, work stations, movement patterns, critical points, transfer procedures, and materials location and support.

With the desired layout of the building and the list of components, the computer-aided design and manufacturing program can produce an extensive design output. The computer-aided design and manufacturing program uses a systems library of components as the data base. The output of the computer program would provide the following information: a cost estimate of the building, the prefabricated components, and the finishing work; a complete list of materials required; a schedule of the activities; the production plans for the prefabricated components at the plant; the distribution of the drawings and specifications to the construction and production teams and to the building site; a complete set of transportation plans for the packaging and dispatching the prefabricated components from the factory to the work site; the robotization programs for on-site utilization in terms of robots to be used, work areas, work stations, supply materials, and transfer points; the progress and cost control reports for work both on the site and in the factory; complete listing of payments, billings, and accounting associated with the production plant and the construction on the site.

CHAPTER SEVEN
ACTUAL APPLICATIONS IN CONSTRUCTION

7.1 GENERAL

The lack of construction robots is quite alarming considering the facts that the United States has the lead in computer related technologies, artificial intelligence research and limited robotic technologies. Many foreign countries have put a high priority on robotic construction research and have developed robots that have been performing econmically useful tasks for construction contractors. The Japanese have developed a robotic homebuilding industry and an automatic assembly robot system for use in shield tunnel excavation work. The British have developed a robotic submarine trenching machine for laying cables on the floor of the English Channel. The Netherlands has developed a robotic gas metal arc welding system for use in the construction of offshore platform decks. Finland has developed a hydraulic multi-jointed manipulator that can be used in uncertain and changing environments.

7.1.1 Robotic Homebuilding

Through the use of robotics, the Japanese are going to become the world's most advanced builders of manufactured homes. Japan uses robots to build homes because its industrialized homebuilding industry depends upon high-volume production. (8-18)

Manufactured housing is not too different from discrete parts manufacturing and assembly. An automatic wire-guided vehicle system is used to move parts from a raw material storage area to a cutting area, to a subassembly area, to an assembly area, to a finishing area, to a packaging area and to a finished storage area. At each stopping point along the way, robots cut, insulate, assemble and weld. Robots are used to load and unload the automatic wire-guided vehicle system and they are also used to position sills, studs, headers, fire stops and braces. Some of the other activities that the robots perform are: nail panels to frames, drill holes for electrical wiring and plumbing pipes, install electrical outlet boxes and cut window and door openings.

One Japanese company, Misawa Homes, has developed ceramic wall panels composed of concrete and silicate. The panels are fireproof and soundproof. Also, the panels are lighter than concrete and cheaper to produce by robotics than wood panels. (8-19)

The Japanese builders have been able to cut costs and increase productivity by using robots to standardize the production of building components. Sixty percent of all Japanese homes use standardized steel frames which are produced by robots. At least eighty percent of the building components are common to all homes. The same robotics manufactured building components go into multi-family homes as well as single-family homes.

Japanese home buyers are rejecting the ready made homes in favor of the custom designed homes. The reason for this can be attributed to the computer and robotics. The home buyer utilizes a computer to choose from a broad selection of housing elements. The computer generates views of the home along with the lists of parts and prices and a complete set of drawings. The robots then customize the home while it is still on the assembly line.

A new home rolls off the automated assembly line every forty minutes. The computers manage the manufacturing and assist in keeping the inventory to a five day supply.

Such success in the robotic homebuilding industry can be directly attributed to the commitment made by the Japanese government and industry to provide systematized construction techniques and space efficient home designs as well as new building materials.

7.1.2 Automatic Assembly Robot System

The Japanese have developed an automatic assembly robot system for use in shield tunnel excavation work. This system automates the complete cycle from part conveyance to assembly and bolt tightening.

The systems consist of a robot, a segment feed, a control panel, a manipulation panel, and a hydraulic power unit. The robot is mounted at the tail of the shield tunnelling machine and serves to assemble the segments and tighten the bolts. The feed system is mounted at the upper part of the trailing cart. It serves to stock segments and to feed these to the robot one after the other. Optical fiber cables are used to connect the control panel to the robot and the other parts of the system. A microcomputer is used for programmed position control and sequence control. The manipulation panel is used to select either manual or automatic modes of operation. Hydraulic power units are installed on the lower part of the trailing cart inside the tunnel and supply hydraulic pressure to the robot. (9-49)

The robotic assembly system works as follows. The robot is fed with a segment from the feed system with the segments grasping part lying directly above the robot. The robot uses a fixation system to firmly attach the supplied segment in its correct position. The robot then utilizes three motions of turning, extension, and sliding to rough position the segment. Then the robot does the fine positioning through the three motions of rolling, pitching and heaving in order to reach a hole matching accuracy of ± .2 mm. After hole matching, all bolts and nuts of a single piece of segment are tightened simultaneously, by means of the bolt tightening machine for which the torque can be adjusted by the robot. The process is then repeated to complete the ring of segments.

This system has generated numerous advantages for shield tunnel excavation work. It has improved safety, segment assembly work can be accomplished unmanned. This system provides greater accuracy. Through the use of the microcomputer the position control can be employed to an accuracy of ± .2 mm. The system operator also serves as the shield machine's operator. There is the need for only one worker to shift the segments from the cart to the feed system. Assembly of the segments is accomplished faster at a fixed rate of accuracy. This results in completion of shield tunnel excavation work in a shorter period of time. A ring of segments can be completed in thirty minutes, regardless of the diameter of the segments. Also, this system produces a better quality of work. Through the use of contant bolt tightening torque and prevention of concrete segment chipping, the water leakage from joints is reduced. There is no accumulation of individual fitting errors when assembling the segments.

Robotics has been successfully utilized in the Japanese construction industries. Despite the high initial cost factor, the payback periods have been short enough to make this robot-based system feasible. (9-49)

7.1.3 Robotic Rock Trencher

The British have developed a 176 ton robot trencher that is cutting two four feet deep trenches across the English Channel to France. These trenches will hold power cables to link France and the United Kingdom. The robot utilizes three underwater cameras and two sonar units which are controlled from a barge overhead. The cameras and sonar provide the robot with the necessary information to determine the depth of the trenches and obstacles in the path of the trencher. The robot is propelled along the bottom of the English Channel by a track mounted system.

This electrical link is extremely important to both countries. The link will offer the two countries the advantage of trading electricity at times when one system is producing power more economically than the other.

The use of the robotic trencher was chosen because of the possibility of hitting an unexploded mine or torpedo in the channel. The project was completed nearly six months ahead of schedule and this accomplishment was directly attributed to the robotic trencher.

7.1.4 Robotic Welding System

The Netherlands have developed a robotic arc welding system that is being used in the offshore platform building industry. The floors of the offshore platform decks consist of steel plates supported by steel beams. The fillet welds between the beams and the deck plates have to be continuous and watertight to prevent corrosion. (11-387)

The structure of the deck floor is made up of steel floor plating, about 3/4 inch thick, placed on top of a supporting grid of steel beams. The girders and transoms have cross sectional heights that range from

8 inches to 53 inches. The sides of the quadrangle measures between 20 inches and 280 inches. (11-388)

The robot is a preprogrammed first generation robot that uses a single optical profile sensor that ensures an uninterrupted and watertight fillet weld. The platform to be welded is spanned by a gantry carrying the robot trolley. The robot is mounted head down, enabling its effector to reach every corner of the compartment. The preprogramming of the robot consisted of giving it only the starting position. The single optical profile sensor then takes over and completes the welding process in each compartment. The robot trolley must be moved by an experienced welder to each compartment formed by the deck plate and the girders. The optical profile sensor emits a laser beam that is swung across a plane that cross-sections the joint to be welded. At the intersection of the joint and the laser beam the light is reflected and picked up by a linear array camera. The angle of incidence with respect to the camera optical axis is dependent upon the distance between the sensor and the object surface. From this information the camera generates a two dimensional signal of the object surface. The third dimension of the object surface is derived from successive scans when the sensor is moved along the welding path.

The robot uses a torch/sensor unit to produce the fillet weld. The robot hand carries two disks that can be rotated independently from each other and the hand. The upper disk is the sensor disk and the lower disk is the torch disk. The torch is mounted to the torch disk in such a way that the arc itself is located exactly on the common rotation axis. The arc is the tool center point and is the focal point of all guidance commands. The sensor disk provides transverse position information and height information. The robot tracks along the seams and around the corners by way of tracking algorithms preprogrammed into the robot.

The robot has proven to be very efficient and effective in closed path seam welding operations and there is potential for this system to be used in a great deal of applications in the field of flexible automation of welding operations.

7.1.5 Hydraulic Multi-Jointed Manipulator

Finland has developed a hydraulic multi-jointed manipulator that uses real-time information in the control method. This control method allows about two degrees of freedom in the manipulator's motion, the ability of automatic movements, and the capability to change the recorded path or teach the robot a completely new path. This control method was developed for manipulators used in uncertain and changing environments, such as the logging industry.

The robotic manipulator is controlled in the Cartesian coordinate system. The operator, computer, and the mechanical boom system form a semi-autonomous manipulator system. (12-228) The role of the operator is to supervise the manipulator system, to solve problems caused by the unknown environment and to relay the functional plan to the computer. The operator uses joysticks to control the motion of the manipulator. The speed and direction of the manipulator's end point motion is analagous to the movement of the joysticks. The computer converts the operator specified movements to joint angles and outputs these as commands to the joints of the manipulator. The manipulator can be operated in either manual or automatic mode. In the automatic mode, the last recorded trajectory is repeated. The manual inputs are scanned and evaluated and the operator has the capability of manually deflecting the manipulator's end-point a minimal distance off the recorded track. This is a useful feature because obstacles that have not been taught before can be avoided without teaching the manipulator a new trajectory.

This system has proved useful because the operator can control all of the operations more effectively: the processing unit, the boom con-construction and the steering of the log forwarder. The processing time for each tree has been reduced since the operator can easily handle the boom system and automatically feed the tree to the processing unit while the forwarder is in motion.

7.1.6 Robotic Fireproofing

Japan's Shimizer Construction Company is using a computer controlled manipulator to apply fireproofing insulation in building construction. (7-197) The manipulator arm uses a potentiometer sensory unit as its position sensor. The spray nozzle is mounted on the end of the manipulator. The spray nozzle combines the proper mixtures of rock wool and cement milk. The proper mixture is controlled by the computer. The manipulator is mounted on a traveller which has a variable length capability of 20 inches. The traveller uses distance sensors and has a 90 degree range of motion.

CHAPTER EIGHT
SOCIAL IMPLICATIONS

8.1 GENERAL

The primary social implication of the use of robotics in construction is the threat of widespread unemployment. The use of robotics in construction will require a major reorganization of the building construction process. This would result in the displacement of labor and redefining the tasks of others. Immediately, job security becomes a major concern of construction labor. Nevertheless, this threat to unemployment is more emotional than real. Take for example, the manufacturing industry which utilizes an enormous amount of robots. Only 0.06 percent of blue collar jobs were replaced by robots. Jobs were created in fields related to robotics. Manufacturing productivity increased also, while working hours decreased. (13-229)

The key to robotization is to ensure the cooperation of labor. A lack of cooperation will render the robots ineffective. In an effort to foster cooperation, a study should be conducted by owner and by labor together, prior to the implementation of robots. This study should concern the policies and priorities of implementation. The following factors should be considered during the study. The current supply and demand of labor in more hazardous tasks and in harsh weather conditions. The age and personal characteristics of the various building trades. The attitudes of unions in different building trades to alternative scenarios of robotization. (4-277) A concerted effort by all concerned will result in effective uses of robotization.

Another social aspect of robotization which cannot be overlooked is the attitude of the lower level management to the changes brought about by this process. The attitudes in construction management tend to be very conservative. There is always the tendency to use old and proven solutions rather than innovative methods and technologies. Therefore, the support of management, as well as labor, must be obtained in order to reach the expected results of robotization.

Whatever the implications, though, any construction company that resists robotics on whatever grounds will find itself competing with other companies that are willing to accept those same implications and are committed to the benefits of robotics.

CHAPTER NINE
ECONOMIC IMPLICATIONS

9.1 GENERAL

The success of any commercial undertaking has to be measured in terms of financial performance. No matter what the social benefits are, no matter how clever the technology, no matter how nice the robot is to watch, every proposed investment in robotics has to pass the test of a critical financial analysis.

Investment always involves risk. Appraisal techniques seek only to reduce the uncertainties. No method exists that can remove the element of chance. It is well to remember that all appraisal techniques rely on the accuracy of the input data, some of which has to be estimated or forcasted. It is difficult to examine the economic feasibility of construction robotics which have yet to be developed and processes which have to be reconstructed for optimal utilization. The estimations used will be taken from an industrial robot which is similar in design. The economic factors that need to be considered in an economic analysis are: costs and benefits, value estimation, payback, and return on investment.

9.1.1 Costs and Benefits

The following areas provide a framework for analysis of the costs and benefits of construction robotization; acquisition costs, investment costs, installation costs, maintenance costs, operation costs, labor savings benefit, quality improvement benefit and elimination of hazardous conditions benefit.

9.1.1.1 Acquisition Costs

The acquisition cost of a robot is highly variable, depending upon the number of articulations, sphere of influence, weight handling capability and control sophistication. It appears that the purchase price of the general purpose robot, mentioned in Chapter 6 is about $100,000. The two types of surface finishing robots do not employ a jointed manipulator and therefore their configuration is much simpler and their cost conceivably lower. The assembly robot is not structurally different from that of a regular piece of construction equipment. The only difference is the additional robotized activities brought about by the effector, control unit and possibly sensors. The expense of the assembly robot is the least of the four.

9.1.1.2 Investment Cost

The investment costs include depreciation and the interest on the investment. The interest on finance charges on investments are figured in two ways. One is using the current cost of money and the other way is by using the expected return on investment.

Robots, like other equipment, will exhibit a useful life and it is ordinary practice to depreciate the investment over this useful life. The anticipated economic life of 5-10 years for industrial robots may be somewhat shorter for construction robots operating under rugged environmental conditions. In most instances, straightline depreciation is used, but tax schemes may involve depreciation weighted to early years, for example, double declining balance. Special tax credits to encourage capital investment may also influence the cost justification and the buying decision.

9.1.1.3 Installation Costs

The installation costs include the set-up of the equipment at the work site, the running-in, learning expenses and programming expenses. The construction robot will operate from different work stations, and therefore its installation costs will be mainly the learning expenses of the operators.

9.1.1.4 Maintenance Costs

To keep a robot functioning in tip-top shape, there is a need for regular maintenance, a periodic need for overhauls, and a random need to correct unscheduled downtime incidents. A rule of thumb for well designed production equipment operated for two shifts continuously is a total annual cost of 10% of the acquisition cost. For construction robots, this is probably a good estimate to use, due to a construction robot's operation under rugged environmental conditions.

9.1.1.5 Operation Costs

Operating costs are the expenses of the electricity consumed by robotic work. The operating power can be easily computed as the product of the average power drain times the hours worked. Also included in operation costs is the expense of transfering the robots from one work place to another.

9.1.1.6 Labor Saving Benefit

The prime issue in justifying a robot is labor displacement. Construction should be mildly interested in shielding workers from hazardous working conditions, but the key motivator is the savings of labor cost by supplanting a human worker with a robot. Labor costs include wages, fringe benefits, and other expenses of labor. So much the better if a robot can perform for more than one worker and thereby multiply the labor savings potential.

9.1.1.7 Quality Improvement Benefit

If a job is in a hazardous environment, or is physically demanding, or is simply monotonous, there is a very good chance that the quality of work will suffer with the mood of the human worker. A robot would be more consistent on the job and produce a higher quality output. This quality output would be reflected in material savings due to higher precision and better performance of the finished product.

9.1.1.8 Elimination of Hazardous Conditions Benefit

The benefit of eliminating or reducing human involvement in hazardous and strainful tasks can be measured in the smaller number of injuries, increased productivity and fewer work stoppages.

9.1.2 Value Estimation of Construction Robots

The economic analysis must be concerned with the value of the construction robot to the user. The value of a construction robot is defined as the highest price the user may be willing to pay for it while still retaining economic advantage from its use. (14-76) The value can be calculated as the present worth of the direct savings realized from robot employment less the associated expenses. An example of the value estimation will be provided in the next section. (14-76)

9.1.2.1 Value Estimation Example

The value will be calculated as the present worth of the direct savings realized from robot employment minus the associated expenses. The following parameters are used in the evaluation:

a) Economic Life of the robot is assumed to be 3-5 years. The salvage value is assumed to be negligible.

b) Real Interest Rate was assumed as 7-10%. This corresponds to a market rate of 13-16%. The inflation rate assumed as 6% per year.

c) Maintenance Costs were estimated as $10,000 per year. This assumption takes into account the high wear of equipment in construction work and is agreeable with the rule of thumb of 10% of the acquisition cost.

d) Operating Cost was estimated as $1 per hour of operation or $1700 per year of use.

e) Transfer Cost of the robot between two different floor levels was estimated as $50, one hour of two workers. Assuming one transfer every two days the total cost would be $5000 per year.

f) Amount of labor would be estimated only after a detailed design of the robotized process. Manufacturing studies cite a replacement ratio of 1 robot per 1.3-1.5 workers. The ratio for construction is higher due to the poorer work organization, lower extent of mechanization, worse working conditions and greater physical effort, all of which create a higher potential for improvement. For this example, the ratio of 1-2 workers (1700-3400 hours per year) per robot is used.

g) Cost of Labor saved per hour was estimated to include the following components.

Wages including fringe benefits averaged $20.50 per hour for the various trades of skilled workers in the United States. (15-344)

Workmen's Compensation averaged 8.6% of the wages for all trades in the United States. (15-345)

Other Tax and Insurance averaged 13.3% of the wages.

Tools and other equipment used on site costs were 1% of the wages.

Labor related overhead averaged 15% of the wages but only 30% of this overhead is included in labor savings or 4.5% of wages.

The wages and additional expenses amounted to $26.10 per hour. The total annual savings for one replaced worker, assuming 1700 hours per year, is estimated as $44,370.

h) Tax Deduction Due to Depreciation: with depreciation allowance being a tax deductible expense, it effectively increases the net income to the user. At a tax rate of 50%, the annual income is effectively increased by 10% of the investment for robot life of 5 years and by 16% for robot life of 3 years.

The following equation can be used to calculate the value of the robot.

$$V = (kL - M - 0 - T + rP)\,\frac{(1 + i)^n - 1}{i\,(1 + i)^n}$$

V = discounted net worth of service discounted over its entire economic life.

P = initial investment in the robot.

L = saved labor cost per year per one replaced worker

k = number of replaced workers

M = cost of robot's maintenance per year

0 = cost of robot's operation per year

T = cost of robot's transfer per year

r = tax deduction rate (10%-16%)

i = interest rate (7%-10%)

n = economic life of the robot (3-5)

ROBOT VALUE TO USER ($)

Labor Saved (Workers)	n = 3		n = 5	
	i = 10%	i = 7%	i = 10%	i = 7%
k = 1	109,098	115,129	143,557	155,275
k = 1.5	164,269	173,349	227,655	246,237
k = 2	219,439	231,560	311,754	337,200

Table 2 Robot value to user under different assumptions

The value of a robot to user calculated under different assumptions of economic life, labor saved, and interest rate, are presented in Table 2.

From Table 2, the value of the robot varies from $109,098 to $337,200.

The value is particularly sensitive to changes in economic life cycle and the number of workers replaced. It is less sensitive with respect to the interest rate.

9.1.3 Payback Method

This is the least complicated method for assessing the viability of a new project in financial terms. If the payback period indicated is very short, the result gives positive incentive for proceeding with the project, and it is not strictly necessary to use any more complicated appraisal methods. (6-107)

The formula for the payback method is:

$$P = \frac{I}{L-E}$$

9.1.3.1 Payback Method Example

Payback formula $P = \frac{I}{L-E}$

where P = payback period in years

I = total capital investment in robot

L = annual labor cost replaced by robot

E = annual expense of maintenance

Using the information from the value estimation section where

I = $100,000

L = $ 44,370

E = $ 10,000

Therefore,

$$P = \frac{100,000}{44,370-10,000} \qquad P = \frac{100,000}{88,740-10,000}$$

$$P = 2.91 \text{ years} \qquad P = 1.27 \text{ years}$$

This means that the payback period is 2.91 years for one replaced worker. But the payback period is 1.27 years for two replaced workers. Therefore, considering an economic life of 3-5 years, the investment in robotics would seem to be a good, sound venture if the robot is able to replace more than one worker.

9.1.4 Return on Investment Evaluation

Robots should be considered to be as general purpose equipment. Their flexibility means that they can be redeployed as the work dictates. Their reliability indicates a long working life. It is not unreasonable to assume that the construction robot will last for 5 years. Since the investment is going to produce useful work over a period of years, changes in the value of money, interest payable, and the rate of return on the money invested all provide factors that can be evaluated and considered in a project approval or rejection decision. The easiest way to approach this problem is to decide the rate of interest or other return that company policy dictates for its investments, and then ensure that the expenditure at least meets those expectations. (6-107)

9.1.4.1 Return on Investment Example

For the return on investment example, all of the previously mentioned values are used. An additional value is used in this calculation. The total value of the investment is written off by equal investments over the life expectancy of the robot. The equation for the return on investment is:

$$ROI = \frac{S}{I} \times 100$$

where S = annual savings (Labor Costs - Robot Costs)

I = investment

Investment	I = $100,000
Annual depreciation 5 years, straight line	= 20,000
Annual upkeep	= 10,000
Total hours	= 1700/year

<u>Robot Costs</u>

Annual depreciation	$20,000
Annual upkeep	<u>10,000</u>
Total annual robot costs	$30,000

<u>Labor Costs</u>

Wages, including fringes	Annual Cost
$25.00 per hour	$42,500
$25.10 per hour	44,370
$27.00 per hour	45,900

<u>Annual Savings</u>

$25.00	$12,500
$26.10	14,370
$27.00	15,900

$$ROI = \frac{S}{I} \times 100$$

$25.00	12.5%
$26.10	14.4%
$27.00	15.9%

By any standards, the predicted return rates are acceptable. A contributary element to these predictions is the longevity and a freedom from early obsolescence demonstrated by robots, without which the initial investment could never have been written off in small installments, over a longer period of time.

9.1.5 Economic Implications

It was estimated that the value of a construction robot to the user, under normal working conditions, to vary between \$109,098 and \$337,200. This variation is dependent on the economic service life of the robot and the amount of labor saved by its employment.

The lower limit of the expected economic life of a manufacturing robot is 5 years, which is also the lower limit for the economic service life for most types of major construction equipment. There is no reason that a construction robot cannot be designed, at the development stage, for a 5 year economic service life.

Assuming the average productivity of the robot to be 50% higher than that of a worker, the value of a construction robot to the user, would be \$227,655-\$246,237, with a 5 year life span.

Assuming a 5 year economic service life, the results from the payback method of evaluation indicates that the investment in a robot would be sensible. For one replaced worker, the payback period would be 2.91 years and if two workers could be replaced by a robot, the payback period would be even better at 1.27 years.

All of the previous indicators are backed up by the return on investment calculation. At the stated labor rate of \$26.10, an investment of \$100,000 would result in a return of 14.4%. The construction robot is a good investment.

Based on all of the above estimates, it seems that at the present stage of technology and development, robotization has a very good chance of economic viability, when applied to well-adapted construction sites, given thoughtful design, good maintenance procedures, and an adequate work volume.

CHAPTER TEN
CONCLUSION

10.1 CONCLUSION

Robotization will definitely provide a valuable contribution to the construction industry. This contribution will be felt as associated benefits to owners, contractors and labor. The benefits will be greater productivity, higher quality, safer working conditions, and sound economic feasibility. Robots will have a major impact on the technology and structure of the building construction industry.

The employment of robots in construction will require a reorganization of the building construction process. Attitudes, strategies and materials will have to be altered to meet the demands of robotization. Attitudes, mainly low level management, will have to be receptive to the robotic worker. Acceptance of the robot and cooperation on the work site will allow the robot to operate effectively. Conservative ideas and trends will have to be modified. Building strategies and labor strategies will have to be altered. New building methods will have to incorporate robotics on the work site. Labor relations will have to be developed taking robots into consideration. Materials will have to be restructured to facilitate the robots' methods of grasping, positioning and handling. New materials will have to be developed for easier use by the robots.

There are two reasons for doing all of this reorganization work. One is the construction industry statistics and the other is that many foreign countries have already reorganized. The statistics don't lie. Construction, without robotics, the largest single industry in the United States economy has had a steadily declining productivity rate for the past ten years. Also, the total output per worker is lower than the industrial average and construction wages are higher than the industrial average. There are national economic reasons for reorganization. Japan, for instance, has robots that are performing economically useful tasks in the field for construction contractors. Major Japanese engineering contractors are making construction robots a high priority area in their research facilities. When the benefits of robotics are realized in the United States, builders and contractors will be demanding robotic systems. They will have to solve this problem by importing the systems from foreign countries. This could become one more area of technological advancement that Americans could give up without really trying.

The responsibility, for the employment of robots in construction, rests on the shoulders of owners, builders, labor, manufacturers and society itself. The time is now to reorganize, research and develop the systems necessary to effect the use of Robotics in Construction.

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